Earth Planets Space, **52**, 1183–1186, 2000

Evaluation of the candidate Main Field model for IGRF 2000 derived from preliminary Ørsted data

F. J. Lowes[1], T. Bondar[2], V. P. Golovkov[2], B. Langlais[3], S. Macmillan[4], and M. Mandea[3]

[1]*Physics Department, University of Newcastle, Newcastle Upon Tyne, NE1 7RU, U.K.*
[2]*IZMIRAN, 142092 Troitsk, Moscow region, Russia*
[3]*Institut de Physique du Globe de Paris, Laboratoire de Géomagnétisme, 4 Place Jussieu, 75252 Paris Cedex 5, France*
[4]*British Geological Survey, Murchison House, West Mains Road, Edinburgh, EH9 3LA, U.K.*

(Received February 14, 2000; Revised May 24, 2000; Accepted May 24, 2000)

On this occasion the selection of the IGRF for 2000 was left to a small Task Force. Before it was accepted by the Task Force as IGRF 2000, the final candidate model (a truncated version of Ørsted(10c/99)) was compared with a comprehensive set of independent surface and satellite data. The method, data selection, and results of this comparison are described.

1. Introduction

At its meeting in Birmingham in 1999, IAGA Working Group V8 decided that none of the candidate models proposed for IGRF 2000 was good enough. (Comparisons between the candidate models, and with the models and other data, were all much poorer than on previous occasions.) However it was hoped that the apparent problems with the vector data from the Ørsted satellite would be overcome soon, and a small Task Force was set up to produce IGRF 2000 to a deadline. As reported in Lowes (2000), the final candidate model considered by the Task Force was in fact based on Ørsted vector and scalar data. This paper reports on the numerical assessment of this final candidate model, done by comparing it with independent recent measurements.

The next section outlines the method. Then Section 3 describes how the data for the comparison were selected, Section 4 gives the results of the comparison, and Section 5 discusses these results. The Appendix describes the various tests used to eliminate faulty Ørsted scalar data.

2. Test Method

Evaluation of IGRF candidate models is now a well established tradition. It is usual to test the models with data which is as recent as possible, with respect to the date of the model. With only one main-field candidate model to be considered, our work was more the validation of the model that an evaluation.

The IGRF candidate being tested, locally called IGRF2000c, consisted of the constant internal terms of the model Ørsted(10c/99) truncated to $n \leq 10$; it was for epoch 2000.0. (For details of the parent model Ørsted(10c/99), see Olsen *et al.* (2000)) The model was tested against several independent datasets by comparing the field predicted by the model at the appropriate locations with the real data (updated to the same epoch). The residuals were computed and plotted. In doing so, we were trying to see if there were any inconsistencies or regional errors.

3. Data Used for Testing the Model

The first and essential step in the model evaluation was to ensure that the control data used were of good quality. As the model was for epoch 2000.0, data were updated to this epoch, using the secular variation (SV) of IGRF 1995. We used both satellite and ground data for the tests.

3.1 Ørsted scalar data

All the available vector data (from the Compact Spherical Coil magnetometer, CSC), and some of the scalar data (from the Overhauser magnetometer, OVH), of the Ørsted satellite, had already been used in deriving the model; we used the remaining scalar data for our comparison. Two of the current authors (BL and MM) were directly involved in this satellite project, as Institut de Physique du Globe de Paris (IPGP) was scientifically in charge of validation of the OVH data, used to assess the long-term validity of the CSC magnetometer. During the satellite commissioning phase, some problems were found and notified to the Ørsted Science Data Center (OSDC). However, not all the errors had been removed, and we decided to apply further tests before using this OVH data.

Three tests were performed, based respectively on the first and second differences of successive field values, and the comparison of the real data with predicted values. These tests were chosen because of the type of errors involved: most of them were due to the allocation of wrong times to the data. The Appendix describes these errors, and the way they were detected and removed.

After the screening described above we looked at all available data, i.e. from March 16th, through September 30th, except that already used in the derivation of the model. Only night-time data was used, so as to reduce the effect of the diurnal variation of the external component of the field. Further

Table 1. Monthly comparison of model with other 1999 Ørsted F data (all field values in nT).

	$lsa = 0$			$lsa = 1$			$Am \leq 5$ nT		
Month	No.	Mean	St. dev.	No.	Mean	St. dev.	No.	Mean	St. dev.
March	58238	5.5	14.6	145859	7.2	16.4	121052	4.5	16.2
April	64655	5.4	17.7	261441	5.2	20.4	162378	4.8	17.9
May	36374	6.5	15.3	196861	5.7	18.7	83564	4.7	18.2
June	90409	4.9	12.7	278284	4.3	16.8	204989	3.7	16.0
July	125186	4.5	16.6	140734	3.8	19.0	227983	3.5	19.0
August	42976	5.1	20.7	141358	5.8	24.4	78353	3.0	21.3
September	15015	7.0	25.3	81097	7.7	26.3	28599	4.6	26.3

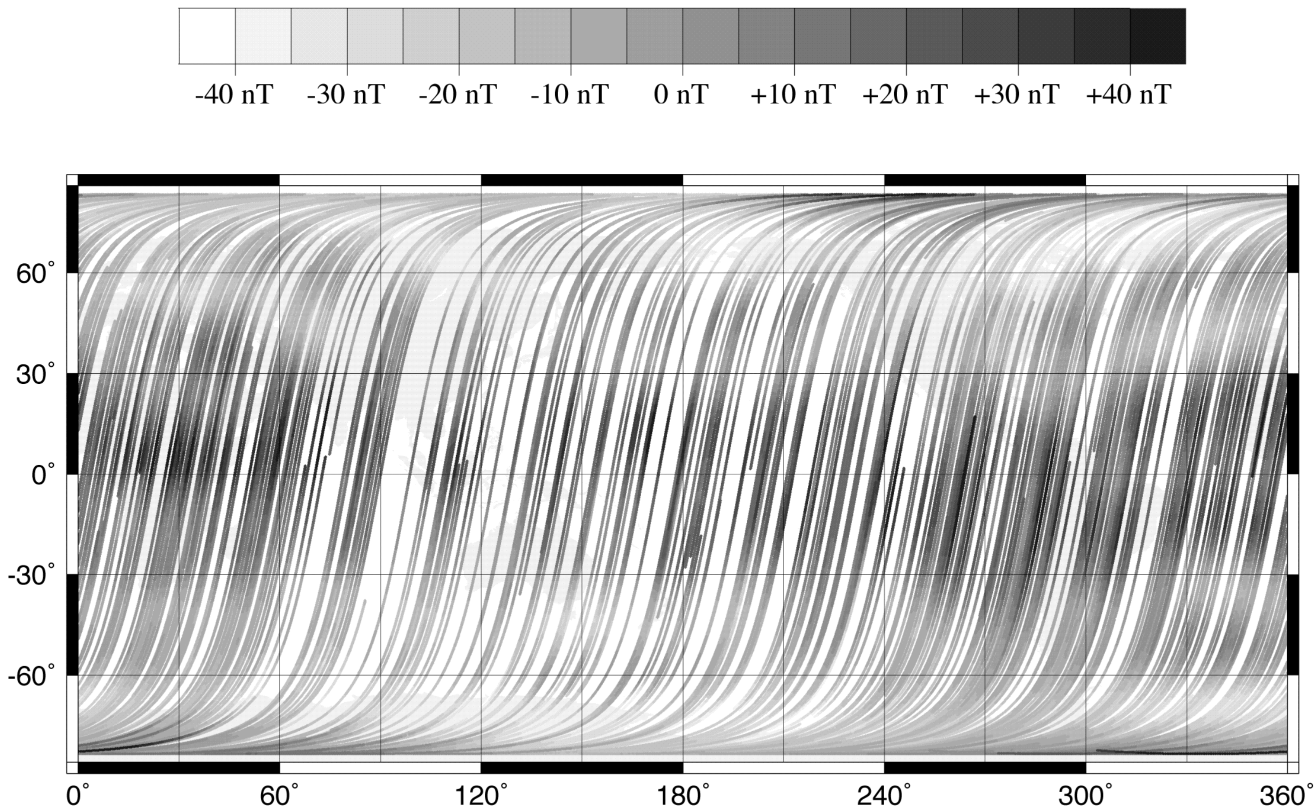

Fig. 1. The residuals (Ørsted F—model) for $Am \leq 5$ nT (Table 1, all months) plotted against position. The large-scale variation probably comes mainly from the omission of the external terms.

selections were made with respect to two indices of external activity. The first of these is the planetary index (Am); the second is the longitude sector activity index (lsa), kindly provided by the Centre d'Etudes des Environnements Terrestres et Planétaires (CETP), as quick-look indices (Menvielle and Berthelier, 1991). These indices were chosen because of their ability to quantify the external activity and because they are available in near real-time. The Am index is a three hour index, expressed in nT. The lsa index is also a three hour index, expressed on the Kp scale. We used four longitude sectors in the Northern hemisphere, and three in the Southern hemisphere.

3.2 Ground data

All the recent ground data available to the British Geological Survey and the IPGP were used. For observatories where monthly mean values were available these were checked and updated to 2000.0 using the exponential prediction method of Langlais and Mandea (2000). Where only annual means were available these were checked, and the last one updated to 2000.0 using the IGRF 1995 SV model. This gave a total of 174 sites. For the 150 of these for which the 1980.0 values were available, these were compared with an $n \leq 13$ 1980.0 model based on MAGSAT data to estimate the observatory bias (the crustal field at this site) and this bias estimate was subtracted from the 2000.0 value before the assessment.

There were also 712 recent repeat station measurements (of which 3 were only total intensity data), and 109 scalar measurements (mainly marine ones, but with some Antarctica values). These were also updated using the IGRF 1995 SV model (see Langlais and Mandea (2000) for more information).

4. Results

The results are given separately for each data type, i.e. satellite, observatory, repeat station or marine and other scalar sources.

4.1 Ørsted scalar data

The results are presented in Table 1, which gives monthly values of the mean and standard deviation of the residuals for each of three datasets, based on different values of the lsa or Am indices.

Figure 1 shows the residuals for $Am \leq 5$ nT (Table 1, all months) plotted against position. This illustrates clearly that on average there is a large-scale variation with latitude, even for data not used in the modelling.

For the quietest dataset the mean deviation is about 5 nT, and the standard deviation about 15 nT. This latter figure is considerably larger than the expected error of the observations. However it must be remembered that the comparison was with the purely internal, $Dst = 0$, truncated $n \leq 10$, model. Sabaka (private communication) had shown that while the earlier Ørsted(9/99) model fitted a sample of independent data with rms of 7 nT, that value increased to 18 nT when the same truncation was applied. Also, while only quiet times were used, some months were quieter than others, so there is probably no significance in the variation from month to month. Similarly, the large-scale variation with latitude seen in Fig. 1 probably comes mainly from the omission of the external field terms.

This would mean that we explain most of the MAGNITUDE of the figures in the Table by the omission of $n = 11$, 12, 13 internal and $n = 1$ external terms, and explain the large-scale nature of the residuals in the figure by the omitted external terms.

4.2 Ground data

Table 2 gives the results of the comparisons for observatories, Table 3 for repeat stations, and Table 4 for the marine and other scalar data.

5. Discussion and Conclusion

We believe that the data we used in this comparison were more thoroughly tested than has been usual in the past. None of the comparisons reported in the previous Section gave any evidence of the residuals being larger than would be expected for each type of data. Although Fig. 1 (and other evidence, see for example Olsen *et al.* (2000), and Lowes (2000)) suggested that the model and/or the Ørsted data did have some puzzling features, these were all of small magnitude. As a result of the numerical comparisons of this paper, and of other considerations reported in Lowes (2000), the Task Force decided that the tested model was good enough to be accepted as IGRF 2000.

Acknowledgments. Map has been plotted using the GMT software (Wessel and Smith, 1991). This is IPGP contribution 1706.

Table 2. Comparison of model with observatory data: (*a*) statistics for Dataset 1 (174 observatories without crustal biases) (*b*) for Dataset 2 (150 observatories with crustal biases).

	a		*b*	
Comp.	Mean	St. dev.	Mean	St. dev.
X	−58	362	7	47 nT
Y	−28	292	4	62
Z	−35	455	−8	110

Table 3. Comparison of model with repeat station data.

Comp.	No.	Mean	St. dev.
X	709	−17	138 nT
Y	709	−35	142
Z	709	−48	211
F	3	−152	112

Table 4. Comparison of model with scalar data.

Comp.	No.	Mean	St. dev.
F	139	33	183 nT

Appendix. Test of Ørsted Data

In the following, we describe the errors and the way we detected them. The reader is referred to Langlais *et al.* (1999), for a complete description of the problems.

The largest errors (up to several thousands of nT) are linked to a software problem that occurs during the magnetometer frequency calibration. From time to time (now once a week, but it was more frequent, up to 10 times a day, at the beginning of the mission), the magnetometer is turned off for approximately 60 seconds, while the quartz frequency is measured.

During normal measurement mode, the packet where data is stored on the satellite should be closed when measurement stops, and another packet opened when the magnetometer is turned on again. However, for some unknown reason this did not happen at the times of frequency calibrations; the first measurement after the restart of measurement mode was stored immediately after the last one before the stop. Unfortunately it is not possible to recover the exact time of the wrongly stored data, because absolute time is stored only at the start of the packet, with succeeding data assumed to be (nominal) 1 second apart until the end of the packet 256 seconds later. This problem was mostly solved by the OSDC by removing packets in which there was a frequency calibration, but some small portions of wrong data remained up to the time of this testing of the model.

We removed most of the wrong data by carefully screening the first time derivative of successive values. In normal measurement mode a maximum first derivative of 37 nT·s^{-1} was noted, even during highly disturbed external conditions.

Looking at a sample of outliers having larger residuals than this, we were able to reasonably explain these as due to wrong allocation of measurement time; consecutive measurements were found to be not time consecutive, having a nominal spacing of 1 second, but rather having a time interval of 10, 20 or even 50 seconds. When the spacing was larger than the nominal one, it means that a new packet had been opened and a new time information provided, so that the following field measurements can be considered as correct.

This kind of error can be detected (and then removed) using:

$$\text{if} \quad \left|\frac{F_i - F_{i-1}}{T_i - T_{i-1}}\right| \geq 37 \text{ nT}\cdot\text{s}^{-1} \quad \text{and}$$

$$T_i - T_{i-1} = 1 \text{ s nominal} \tag{A.1}$$

$$\text{then } (F_i, T_i) \quad \text{is removed} \tag{A.2}$$

$$\text{and the following } (F_{i+j}, T_{i+j})_{\,(j=1,t)}$$

$$\text{are also removed until } T_{i+t+1} - T_{i+t} > 2 \text{ s} \tag{A.3}$$

However, this scheme is only useful for 1-second consecutive measurements. We also decided to test the data by comparing them with values predicted from an *a-priori* model. The chosen model was IGRF 1995, updated to the epoch of data using the IPGP secular variation models computed for producing an IGRF 2000 candidate (Langlais and Mandea, 2000). Measurements that differed more than 200 nT from the predicted ones were removed. It should be mentioned that this value is somewhat arbitrary, and means that some, probably correct, polar measurements, made during highly disturbed external conditions, were removed. However, in view of the large amount of data available, these removals were accepted.

Another error was noticed but had not been removed up to now. Studying the second time derivatives of successive time measurements, some anomalous sequences were highlighted. A typical sequence would be, for example, −0.1, 0.1, 0.0, 0.1, 0.0, 0.1, 0.2, 0.0 nT·s^{-2}, having only a small range of values. However we noticed some strange sequences, as 0.1, 0.0, −0.3, 0.8, −0.4, 0.1, −0.1, −0.1 nT·s^{-2}, which we called "scattering". There is no geophysical reason to explain this fact, so we decided to remove such sequences using the scheme:

$$\text{if} \quad \left|\frac{\frac{F_{i+1}-F_i}{T_{i+1}-T_i} - \frac{F_i-F_{i-1}}{T_i-T_{i-1}}}{\frac{T_{i+1}-T_{i-1}}{2}}\right| \geq 0.5 \text{ nT}\cdot\text{s}^{-2} \quad \text{and}$$

$$\begin{cases} T_i - T_{i-1} \simeq 1 \text{ s} \\ T_{i+1} - T_i \simeq 1 \text{ s} \end{cases} \tag{A.4}$$

$$\text{then } (F_i, T_i) \quad \text{is removed} \tag{A.5}$$

$$\text{and } (F_{i-2}, T_{i-2}), (F_{i-1}, T_{i-1}), (F_{i+1}, T_{i+1}), (F_{i+2}, T_{i+2})$$

$$\text{are also removed.} \tag{A.6}$$

At least 5 measurements are removed per scattering occurrence: this is done to remove all the measurements which contribute to the anomalous value, 0.8 nT·s^{-2} in the above example.

References

Langlais, B. and M. Mandea, An IGRF candidate main geomagnetic field model for epoch 2000 and a secular variation model for 2000–2005, *Earth Planets Space*, **52**, this issue, 1137–1148, 2000.

Langlais, B., P. Ultré-Guérard, C. Vernin, M. Mandea, Y. Cohen, and G. Hulot, Ørsted: IPGP commissioning of the OVH magnetometer, *CNES report*, **OERS-RP-0000-0031-IPG**, 28 pp., 1999.

Lowes, F. J., The working of the IGRF 2000 Task Force, *Earth Planets Space*, **52**, this issue, 1171–1174, 2000.

Menvielle, M. and A. Berthelier, The derived planetary indices: description and availability, *Rev. of Geophys.*, **29**, 415–432, 1991.

Olsen, N., T. J. Sabaka, and L. Tøffner-Clausen, Determination of the IGRF 2000 model, *Earth Planets Space*, **52**, this issue, 1175–1182, 2000.

Wessel, P. and W. H. F. Smith, Free software helps map and display data, *EOS Trans. Am. Geophys. Union*, **72**, 441–448, 1991.

F. J. Lowes (e-mail: f.j.lowes@ncl.ac.uk), T. Bondar, V. P. Golovkov, B. Langlais, S. Macmillan, and M. Mandea